NUCLEAR ASPECTS OF NUCLEOSYNTHESIS IN MASSIVE STARS

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Preliminary results of a new set of stellar evolution and nucleosynthesis calculations for massive stars are presented. These results were obtained with an extended reaction network up to Bi. The discussion focuses on the importance of nuclear rates in pre- and post-explosive nucleosynthesis. The need for further experiments to study optical α+nucleus potentials is emphasized.

1 Introduction

Nuclear reactions play a major role not only in the nucleosynthetic processes determining the elemental abundances in the solar system and the Galaxy but also for determining structure and final fate of a star. Massive stars ($> 8M_\odot$) experience a number of burning phases before they explode as type II supernovae after the collapse of the Fe core. Important nuclear reactions in the late burning stages and in the explosion proceed on isotopes experimentally not sufficiently well investigated or on unstable nuclei which cannot be studied in the laboratory. Thus, astrophysics requires a sound theoretical understanding of nuclear reactions and tests our knowledge at the extremes.

Numerous studies have been devoted to the evolution of such stars and their nucleosynthetic yields. However, our knowledge of both the input data and the physical processes affecting the development of these objects has improved dramatically in recent years. Thus, it became worthwhile to attempt to improve on and considerably extend the previous investigations on pre– and post–collapse evolution and nucleosynthesis. Here we present first results for a 15 $M_\odot$ stellar model with improved stellar and nuclear physics. In this report we mainly concentrate on a few of the nuclear physics issues involved, a more extended report including all details of the simulation will be published elsewhere[1,2]. Below, we discuss the prediction of nuclear rates in the statistical model and, specifically, the treatment of α-particle capture on isospin conjugated targets. The importance of obtaining more information on α+nucleus potentials is emphasized separately.

2 Nuclear Reactions

The nuclear reaction network during the explosive phase (as the most extreme case in our calculation) contains about 2350 isotopes and is shown in Fig. 1. It is evident that there are many isotopes far off stability included for which experimental information is scarce. This is even more true in more exotic scenarios such as the r– and rp–processes which involve isotopes close to the neutron– and proton–dripline, respectively. (In our calculations we do not follow the proposed r–process in the ν–wind emanating from the proto–neutron star shortly after the collapse of the Fe core.)

Important are weak reactions and nuclear reactions with nucleons and α particles. Decay data is also available further off stability whereas nuclear reaction cross sections involving nucleons and light ions are practically known only for stable nuclei. The majority of the latter reactions can be described in the framework of the statistical model (Hauser-Feshbach theory) which describes the reaction proceeding via the formation of a compound nucleus and averages over resonances[3]. Many nuclear properties enter the computation of the HF cross sections: mass differences (separation energies), optical potentials, Giant Dipole Resonance widths, level densities. The resulting transmission coefficients can be modified due to pre-equilibrium effects which are included in width fluctuation corrections (see also a previous paper[3] and references therein) and by isospin effects. It is in the description of the nuclear properties where the various HF models differ. In astrophysical applications usually different aspects are emphasized than in pure nuclear physics investigations. Many of the latter in this long and well established field were focused on specific reactions, where all or most "ingredients" were deduced from experiments. As long as the reaction mechanism is identified properly, this will produce highly accurate cross sections. For the majority of nuclei in astrophysical applications such information is not available. The real challenge is thus not the application of well-established models, but rather to provide all the necessary ingredients in as reliable a way as possible, also for nuclei where no such information is available.

*[bb=50 55 792 612,height=16pc]net$_{e}xpl_{m}od.ps$

Figure 1. Reaction network for explosive burning.

2.1 Statistical Model Rates

As the basis for the creation of our reaction rate set we used statistical model calculations obtained with the NON-SMOKER code[3,4]. A library of theoretical reaction rates calculated with this code and fitted to an analytical function — ready to be incorporated into stellar model codes — was published recently[4]. It includes rates for all possible targets from proton– to neutron–dripline and between Ne and Bi, thus being the most extensive published library of theoretical reaction rates to date. It also offers rate sets for a number of mass models which are suited for different purposes. For the network described here we utilized the rates based on the FRDM set.

2.2 α Particles: Isospin Effects

The consideration of isospin effects has two major effects on statistical cross sections in astrophysics[6]: the suppression of γ widths for reactions involving self-conjugate nuclei and the suppression of the neutron emission in proton-induced reactions. Here, we only discuss the former. In the case of (α,γ) reactions on targets with $N = Z$, the cross sections will be heavily suppressed because $T = 1$ states cannot be populated due to isospin conservation. A suppression will also be found for capture reactions leading into self-conjugate nuclei, although somewhat less pronounced because $T = 1$ states can be populated according to the isospin coupling coefficients. In previous reaction rate calculations[7,8] the suppression of the γ–widths was treated completely phenomenologically by employing arbitrary and mass-independent suppression factors. In the NON-SMOKER code, the appropriate γ widths are automatically obtained, by explicitly accounting for $T^<$ and $T^>$ states[5]. The astrophysical importance of α capture on target nuclei with $N = Z$ is manifold. In the Ne- and O-burning phase of massive stars, alpha capture reaction sequences are initiated at ^{24}Mg and ^{28}Si, respectively, and determine the abundance distribution prior to the Si-burning phase. Nucleosynthesis in explosive Ne and explosive O burning in type II supernovae depend on reaction rates for α capture on ^{20}Ne to ^{36}Ar. An α capture chain on such self-conjugate nuclei actually determines the production of ^{44}Ti [9], which contributes to the light curve by its β decay to ^{44}Ca via ^{44}Sc.

*[bb=50 50 792 550,height=16pc]pf$_{m}$*od.ps*

Figure 2. Production factors in the ejecta of a 15 $M_\odot$ star relative to solar abundance.

2.3 α Particles: Optical α+Nucleus Potentials

A further complication in the treatment of reactions on intermediate and light nuclei involving α particles is the limited success in defining an appropriate optical potential, especially for the low energies typical for astrophysical environments. Early astrophysical studies (e.g.[7]) made use of simplified equivalent square well potentials and the black nucleus approximation. It is equivalent to a fully absorptive potential, once a particle has entered the potential well and therefore does not permit resonance effects. This leads to deviations from experimental data at low energies, especially in mass regions where broad resonances in the continuum can be populated[9]. An additional effect, which is only pronounced for α particles, is that absorption in the Coulomb barrier[9] is neglected in this approach. Improved calculations have to employ appropriate *global* optical potentials which make use of imaginary parts describing the absorption. In the case of α-nucleus potentials, there were only very few global parametrizations attempted at astrophysical energies, also due to the scarcity of experimental data in the energy region of interest. The high Coloumb barrier makes a direct experimental approach very difficult at low energies. Current astrophysical calculations mostly employ a phenomenological Saxon–Woods potential based on extensive data[10]. Future improved α potentials have to take into account the mass- and energy-dependence of the potential. Extended investigations of α scattering data[11,12] have shown that the data can best be described with folding potentials. Few attempts[6] have been made to construct such an improved global potential. Nevertheless, the postulation of such an optical potential close to or below the Coulomb barrier remains one of the major challenges. More experimental data is clearly needed.

3 Further Inputs

Further nuclear input were updated rates from experimental cross sections for light as well as heavy nuclei and updated beta-decay rates. New predictions of weak rates[13] were also included. In respect to earlier simulations[14] we also used updated neutrino loss rates and opacity tables (OPAL95), and consider mass loss due to stellar wind. For further details, refer to our other papers[1,2].

4 Results and Summary

For the first time, we studied consistently the production of all isotopes up to Bi during the pre-supernova evolution and the type II supernova explosion of a massive star. Exemplary for our results, the production factors of a 15 $M_\odot$ star are shown in Fig. 2. The revised weak rates introduce an important change mainly during core silicon burning and thereafter leading to an increase of the central Y_e and smaller Fe core masses at the onset of core collapse. In addition to the well-known strong dependence of the stellar structure on the $^{12}C(\alpha,\gamma)^{16}O$ rate, we also found the (α,n)–(α,γ) branching on ^{22}Ne to be an important candidate for further laboratory study. It sensitively determines the strength of the s–process in the SN models.

Summarizing, the progress in predictions of nuclear reactions has made it possible to consistently study the nucleosynthesis in a type II supernova model over a wide range of nuclear masses. The new investigations also underline the importance of new experimental and theoretical studies of specific nuclear properties.

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